Citation for published version:
Ward, P, Gore, J, Hutton, R, Conway, G & Robert, H 2018, 'Adaptive Skill as The Conditio Sine Qua Non of Expertise', Journal of Applied Research in Memory and Cognition, vol. 7, no. 1, pp. 35-50. https://doi.org/10.1016/j.jarmac.2018.01.009

DOI:
10.1016/j.jarmac.2018.01.009

Publication date:
2018

Document Version
Peer reviewed version

Adaptive Skill as the *Conditio Sine Qua Non* of Expertise

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Accepted for publication in the *Journal of Applied Memory and Cognition* Jan 2018
to be published in the Special Section:
Gore, J. and Ward, P. (March 2018). Naturalistic Decision Making under Uncertainty: Theoretical and Methodological developments. *Journal of Applied Memory and Cognition*

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Abstract

This critical interpretive research synthesis is on the topic of adaptation and skill. After an initial identification of 1995 abstracts we identified and collated a database of 140 publications that explicitly reference expertise and adaptation. We found that empirical data on adaptive skill are sparse and the literature base is largely conceptual. We differentiate the adaptive nature of expertise from routine or every day skill, and we redress the balance between what constitutes expertise and when expertise matters. We present an overview of current models of expertise including a project that we completed for the UK Ministry of Defence on the nature of adaptive skill. We discuss implications for future training by presenting empirically based training principles designed to develop adaptive skill. We assert that adaptive skill is the *conditio sine qua non* of expertise and conclude with suggestions for further research.

Word count 142

Key words:
Adaptive skill, expertise, training, critical interpretive synthesis

General Audience Summary

Adaptive thinking is an area of concern for organizations, business, government and society. Very little is known, however, about what makes an expert adaptive, or how the research that is relevant to this question has contributed to our understanding. This paper provides a taking-stock synthesis of the discussions and evidence that involve concepts of adaptive skill. We critically interpret a wide range of literature sources and stakeholder experiences as part of a review completed on behalf of the UK Ministry of Defence (MOD). The MOD is interested in the development of adaptive skills because these will be paramount in dealing with the future character of conflict, which is likely to be highly uncertain, and will present unique challenges as well as opportunities for the way we work. We present an overview of current models of expertise and discuss implications for future training by presenting evidenced-based training principles designed to develop adaptive skill. We assert that adaptive skill is the *essential ingredient* of expertise and conclude with suggestions for further research.

When one thinks of an expert, numerous qualities come to mind: skilled, experienced, knowledgeable, intuitive, effortless, talented, and perhaps even gifted. Experts are often described as those who perform reliably and at a superior level, and perhaps employ qualitatively different reasoning strategies compared to those at lower levels of proficiency. Hence, when an expert fails or is outperformed by a less proficient individual, their status becomes that of a "so-called expert," and even the value of expertise itself might be brought under scrutiny. We openly assert that experts are not infallible but agree with Collins (2017) that it is possible to work out whether someone has the appropriate level of expertise. That does not mean experts will always be successful. Rather, it means that it is incumbent on the scientific community studying expertise, and on society as whole, to be able to separate those who can make effective contributions from those who cannot, and to determine *when* those contributions matter most.

In this article, we present a case for adaptive skill being the *conditio sine qua non* of expertise. We differentiate the adaptive nature of expertise from routine or everyday skill, and attempt to redress the balance between the what (i.e., components of expertise) and when (i.e., when the important components matter most) of expertise. In the first section, we present an overview of some of the earliest research to address the adaptive nature of expertise. In the second section, we present an overview of current models of expertise that capture its adaptive nature. In the penultimate section, we present an overview of a research project on the nature of adaptive skill and its relevance to expertise. Last, we discuss the implications for training, and present a set of training principles grounded in the expertise literature that were designed to develop adaptive skill. We begin by providing an outline of why the superior performance associated with expertise may not always be observable, and when it is, when it is most valuable.

When are Experts Expert?

Although the positive outcomes associated with expertise in most domains are manifest and undeniable, there are circumstances when it might be unreasonable for experts to be expected to perform at a superior level or better than those at lower levels of proficiency. It is important to explain how this can occur. For example, few would expect an expert operating well outside of the specialty domain to know more or do any better than those who work in that specialty area. Experts are often individuals who have particular sub-domain specializations or skills (Hoffman, 1987). Thus, on some cases from within the broader domain, experts may not excel when compared to, say, journeymen. For instance, researchers have shown that when asked to think aloud during routine clinical cases in practice, there can sometimes be no differences in the structure and content of expert and lesser skilled nurses' thinking—both groups rely on pattern recognition that resemble intuitively guided action (e.g., Greenwood & King, 1996; see also Corcoran, 1986; Tanner, Padrick, Westfall, & Putzier, 1987).

In collective decades of experience, researchers have investigated highly skilled individuals operating in complex perceptual-cognitive work—on thousands of trials or cases across over a hundred studies, in representative and naturalistic settings, and across a broad spectrum of domains. There has rarely, if ever, been a case where *every* expert choice, judgment, or inference was made at a reliably superior level, or where the experts performed better on *all* trials. On some trials, all participants have failed irrespective of their skill level, potentially because the trials were too random (cf. Sala & Gobet, 2017), had low ecological representativeness (Hoffman & Deffenbacher, 1993), or were low in ecological validity in the sense there was no useful information in the environment on which to base a decision (Brunswik, 1957). On others, all participants (at different levels of skill) have succeeded, perhaps because the situational outcome or required action was obvious and did not need any special skill to perform. Or, it could be that the task was sufficiently routine or uncomplicated that others at lower levels of proficiency who were suitably practiced (e.g., apprentices, journeymen) could perform successfully and, hence, would act no differently from an expert (Hoffman, 1998). To explain the similarities across proficiency levels in everyday work, Greenwood and King (1996) suggested that routine cases which, by definition, are of high frequency, do not necessarily require experts to access or deploy complex concepts and reasoning of the type thought to typify expertise. The implication is that although expert performance on routine cases is often very evident, the essential characteristics of expertise might be more apparent when engaging in more difficult cases, especially those that occur with relatively low frequency, where adaptation may be necessary (see Hoffman, 1987).

On such cases, experts often do reason differently from non-experts. They perform better, and reliably so. Researchers are able to discriminate them on these cases from those individuals at lower levels of proficiency. As an example, in a simulated study of skilled law enforcement officer decision making on representative tasks, participants were asked to respond to high and low frequency events involving a perpetrator who might be armed. Participants responded just as they would in a real-world setting by determining if and when an escalation of force was necessary, and then by acting accordingly (e.g., communicating with, and issuing commands to the perpetrator, unholstering/aiming/shooting a handgun). Three of the 19 cases were sufficient to discriminate between SWAT-trained and rookie officers (e.g., suicide bomber, hostage situation, and a suspect with an assault weapon inside a school). Although these scenarios were plausible, all three were considered very low frequency events and not necessarily representative of everyday police work (Ward et al., 2011). Hence, although expertise can be studied on routine cases, following others we argue that our understanding of expertise can best be leveraged by examining performance on challenging, low-frequency, non-routine cases where adaptive skill—or the ability to deal with the non-routine—is paramount (e.g., Crandall et al., 2006; Hoffman et al., 2014).

Are Experts Adaptive?

The assertion that the value of expertise is most evident in rare and potentially novel cases poses some interesting challenges for the study of expertise. If experience and practice on rare cases were the determinant of expertise, without intervention it could take a lifetime to accrue the necessary exposure to sufficient numbers of such events to become an expert (Hoffman, Fiore, Klein, Feltovich, & Ziebell, 2009). This would be especially true if it were necessary for rare events to be appositely novel, challenging and complex to permit one to develop the necessary expertise to handle with skill any subsequent cases that were similarly non-routine and challenging. Alternatively, one could assert that expertise acquired on a sufficient number and range of routine cases might engender the ability to adapt to new, non-routine cases. But traditional definitions of expertise suggest that it is highly domain-specific with little evidence of transfer (cf. adaptation) beyond tasks and situations that require familiar reasoning strategies or have a similar environmental structure (e.g., Ericsson et al., 2006). One could argue that the mixed findings on transfer from studies of expertise have to do with: (a) the historical focus on particular types of domains (e.g., chess, music, sports), (b) the focus on the notion that what gets transferred is knowledge or skill, or (c) the way in which transfer has been studied (i.e., a single type of task applied to different problems or cases). It can sometimes appear as if there is no transfer of knowledge or skill, when in fact what has transferred is an enhanced ability to learn when confronted with new kinds of problems (Lobato & Siebert, 2002).

In many modern work domains, the operational environment is increasingly complex and ever-changing, and therefore difficult to predict (see Ward et al., 2016b). As the work environment becomes more volatile there is a need for experts who not only possess the required domain expertise as traditionally defined, but who can also quickly adapt to situational change. To operate effectively in such environments, proficient workers need to be both skilful in carrying out more routine aspects of their work and be able to adapt effectively in unexpected or novel situations (see Hoffman, 1998). They also need to engage at a metacognitive level in goal-conflict resolution to ensure they achieve or revise the desired end goal. Hence, one might think of expertise, not just as the ability to transfer knowledge, skills or procedures to similar cases, or think of transfer as an end state or goal in and of itself. Rather, expertise is a process of continual learning and development—required, in part, because the work itself is constantly changing. From this perspective, expertise is a process of adaptation and the ability to deal with change.

Over the last few decades, Naturalistic Decision Making (NDM) researchers have asserted that to fully appreciate the challenges of complex cognitive work, human performance and cognition should be studied at multiple levels of analysis (i.e., from the level of individual cognitive work to the level of the sociotechnical work system). This paradigm was first presented as NDM because the emphasis was on the decision-making skills and strategies, predominantly of experts performing their work, often in the field. NDM as a community of practice has recognized that its subject matter is *macrocognition* (see Patterson & Miller, 2010), which spans the full range of joint (i.e., by individuals, teams and technological systems) cognitive work as done; rather than work as imagined, anticipated, or as recreated in the laboratory (e.g., Hollnagel & Woods, 1983). The term macrocognition has been defined as adaptation of cognition to complexity (e.g., Klein et al., 2003). By logical extension, one might define expertise as skilled adaptation to complexity. This component of a full conceptual definition of expertise is not new (Hoffman, 1998). However, there is considerable variation in existing research efforts, particularly in their attempt to define adaptive performance in measurable terms, and to operationally define terms related to the adaptive nature of expertise such that we can better understand what it really means to adapt skilfully and successfully.

In 2014, following Alberts and Hayes (2003), we defined adaptivity as "the ability to employ multiple ways to succeed and the capacity to move seamlessly among them" (Hoffman et al., 2014, pp. 51-52). A successful demonstration would be, for instance, where officers in a command and control context are able to "go off plan, but stay within intent." In this earlier work, adaptivity was differentiated from robustness (i.e., ability to maintain effectiveness across a range of tasks, situations, and conditions) and resilience (i.e., ability to recover from the effects of destabilising factors that affect execution during an attempt to reach primary goals), and all three concepts were associated with high levels of proficiency, flexibility, and transfer to novel work situations. However, how such experience supports skilled decision making and/or actual expertise in naturalistic contexts, and how they relate to established definitions of adaptation, transfer, and flexibility has drawn limited attention. In the next section, we review the empirical and conceptual basis of adaptation and examine the genesis of this research with respect to expertise development.

The Empirical and Conceptual Basis of Adaptation and the Origins of the Term "Adaptive Expertise"

To explore the myriad of research that encroaches on the topic of skilled adaptation, we conducted a review of literature to unpack the concept of adaptation. Rather than use conventional literature search methods, we adopted a critical interpretive synthesis approach (e.g., see Dixon-Woods et al., 2006) to specify the scope and bounds of the research to be reviewed (Ward et al., 2016a). After extensive search of concepts related to adaptation (including transfer, flexibility, cognitive flexibility, cognitive rigidity, cognitive agility, creativity, analogy, similarity), we identified several additional concepts that were frequently mentioned in connection with expertise (including metacognition, intelligence, self-efficacy, motivation, personality, teams, organisations, learning, retention, training, and tolerance for ambiguity). We then performed a second wave of searching using 94 search-term combinations. This lead to 1995 abstracts. We then identified those sources most relevant to our goals of understanding adaptation in the context of expertise or its development (*N* = 72). Based on these and secondary citations (e.g., those cited by, or that cited, the identified sources), we established a database of 140 publications related to expertise and adaptation.

Two key findings derive from this review. First, empirical data on adaptive skill are sparse and the literature base is largely conceptual. Where empirical data exist, they primarily pertain to measures of transfer of knowledge (which we have reviewed extensively elsewhere, see Hoffman et al., 2014). Even when authors explicitly stated that an adaptive performance test or assessment of adaptive skill had been implemented, typically the measures used were of transfer rather than of adaptive skill (e.g., Lussier, Shadrick, & Prevou, 2003; Shadrick & Lussier, 2004; Shadrick et al., 2007). Second, although there is a somewhat confusing array of terms used to refer to skilled adaptation of some kind, there is some consensus on the origins of the notion of experts being adaptive, imbued in the term adaptive expertise.

The term adaptive expertise was coined by Hatano and Inagaki (1984/1986). Their work focussed on differentiating adaptive from routine expertise, and was primarily driven by cultural differences (in education) between Japan and western societies. Routine task execution was described as being based on procedural knowledge or skill. Mastery of that procedure—or routine expertise—was described as being "outstanding in terms of speed, accuracy, and automaticity of performance" (see 1984, p. 31). Yet, because the procedures associated with routine expertise were limited to near transfer (i.e., similar procedural problem types within the same domain, especially those that look different but require the same/similar procedures), they concluded that routine experts “lack flexibility and adaptability to new problems” (see 1984, p.3 1). Others have argued that experts are adaptive by definition (Hoffman, 1998). In this view, Hatano and Inagaki’s definition of “routine expertise” is consistent with the classical description of a *journeyman*: an experienced person who has practiced until he can reliably get it right more often than not and can perform competently without supervision.

In contrast to routine expertise, adaptive experts were described by Hatano and Inagaki as those who not only perform procedural skills efficiently but also have a strong conceptual understanding of those procedures and the associated contexts. They argued that having a good conceptual understanding permits the development and use of a context-sensitive strategy where experts can readily identify key decision points in a specific course of action, and judge when variations of an existing procedure might be in/appropriate. Moreover, it allows the expert to immediately access on the fly opportunities to deviate from the outcome path (as defined by the original procedure) by selecting, modifying, or generating anew, alternative courses of action at each procedural step. From this perspective, conceptual understanding is the primary basis for being flexible and adaptive. In brief, Hatano and Inagaki (1984/86) asserted that conceptual understanding of procedural skill affords in-event adaptive thinking.

Their explanation of adaptive expertise, however, was couched in terms of mechanisms similar to those already proposed by others to explain expertise more broadly (for a review, see Chi, Feltovich, & Glaser, 1981). For instance, Hatano and Inagaki suggested that a data-model-based mechanism supports adaptive thinking. Data (or empirical knowledge of the co-variation among variables) is required to permit examination of when original procedures are and are not effective. A model (or an understanding representation/process for elaborating a signal and differentiating it from noise) is required to permit selectivity and efficiency, and to direct effective outcomes. Moreover, they noted the reciprocity in this kind of mechanism, indicating that "the observed data suggest what model should be adopted, and the adopted model constrains what kind of data are to be observed" (Hatano & Inagaki, 1984, p. 29). This idea anticipated Klein's Data/Frame model of sensemaking, which is one of the two central models in Macrocognition (see below).

Although research on the notion of adaptive expertise has continued (e.g., by examining individual difference characteristics; Bohle Carbonell et al., 2014, 2015), the majority of recent research in this area has not empirically examined the nature of the underlying mechanisms (for exceptions, see Hoffman et al., 2014; Feltovich et al., 1997; Klein & Baxter, 2006; Hoffman, Best, & Klein, 2014; also see Ericsson & Lehmann, 1996). In the following section, we review the literature that has examined the kinds of mechanisms that might explain an expert's adaptive skill.

Contemporary Research on Adaptation to Complexity and Adaptive Skill

Based on what has been said so far, it might be thought that the term "adaptive expertise" is tautological (i.e., experts are adaptive by definition). This does not quite end the matter, however. Even exerts are prone to what is called the "reductive tendency." This concept comes from the empirical findings from Rand Spiro and Paul Feltovich's research on cognitive flexibility in medical contexts (e.g., Spiro et al., 1988, 1995; Feltovich et al., 1997). Cognitive flexibility is

> [T]he ability to represent knowledge from different conceptual and case perspectives and then, when the knowledge must later be used, the ability to construct from those different conceptual and case representations a knowledge

> ensemble tailored to the needs of the understanding or problem-solving situation at hand (Spiro et al., 1992, p. 58).

A central feature of Cognitive Flexibility Theory (CFT) is that in order for knowledge to be useful (i.e., highly accessible whenever needed in any relevant context and in a myriad of different circumstances), it has to be experienced, acquired, taught, organized, and mentally represented in multiple ways. When knowledge is not acquired flexibly, its use is limited to situations that resemble the initial learning context, which constitutes a fraction of the situations where that knowledge may be applicable. When knowledge structures are acquired flexibly, knowledge assemblies can be built "to fit the diverse future cases of knowledge application in that domain" (Spiro et al., 1995, p. 67).

A core observation from CFT is that when faced with a challenging problem or situation, problem characteristics, called dimensions of difficulty (e.g., dynamicism, interactivity, concurrence, non-linearity see amongst others) can cause reasoning difficulties for learners, even those at the senior apprentice to junior journeyman level (Feltovich, Spiro, & Coulson, 1989, 1993; Feltovich, Coulson & Spiro, 2001). Frequently, the understanding of complex systems is biased by the reductive tendency to simply. As a consequence, learners often characterize situations too simply with respect to the dimensions of difficulty (e.g., static, non-interactive, sequential, linear). The reductive tendency is an inevitable consequence of learning—since understanding of anything complex will always be incomplete at any given time. This applies to experts, although misconceptions and incorrect beliefs, which are resistant to change and can inhibit learning and future adaptation, are more characteristic of individuals of less proficiency than experts.

Feltovich et al. (2001) referred to the tendency to try to preserve misconceptions as knowledge shields. These are denial or defense mechanisms of a sort. Shields include downplaying the importance or relevance of contradictory data and range in nature, arguing from authority, resorting to bad analogies, ignoring secondary effects, arguing from special cases, and arguing that a principle has restricted applicability. Although these findings emerged in the domain of medicine, similar observations have been made in other domains and applications, including complex systems (e.g., Greeno, Collins & Resnick, 1996), military command and control (Houghton, Leedom & Miles, 2002), and the design of complex sociotechnical systems (Woods, 2002).

Unsurprisingly, cognitive flexibility requires a specific goal, deliberative practice, sustained effort and experience to overcome knowledge shields. Rand Spiro, Paul Feltovich and their colleagues have argued that rather than just focusing on unlearning misconceptions, one way to escape the adoption of knowledge shields is to preserve the functional complexities of the to-be-learned material during learning. This is in contrast to the common instructional technique of oversimplifying the material to be learned and then progressively increasing its complexity. These ideas, in addition to acquiring knowledge flexibly, have been applied extensively in instructional settings (e.g., Jonassen, Ambruso, & Olsesen, 1992). The principles of CFT, along with the conceptual mechanisms adopted by Hatano and Inagaki, are consistent with the mental modelling processes that support skilled adaptation and high levels of proficiency (e.g., Klein et al., 2003), and with the underlying data-frame mechanisms proposed in recent theories of expert sensemaking (Klein et al., 2006).

Sensemaking as a Process of Adaptive Understanding

Klein et al.'s (2006) Data-Frame (D/F) model of sensemaking was designed, in part, to unpack the diagnosis loop described in an earlier related model—Recognition Primed Decision (RPD) model (Klein, Calderwood, & Clinton-Cirocco, 1986, 1988). The RPD diagnosis loop focuses on decision makers' attention to critical cues, plausible goals, and expectancies that allow them to understand evolving situations, ultimately in the service of pursuing a course of action. The D/F model, on the other hand, elaborates the mechanisms involved in situation understanding, and on the act of making a situational assessment (rather than pursuing a course of action). In particular, the D/F model focuses on how individuals make situational assessments in the face of an anomaly or surprise (rather than on the comprehension process supporting situations that evolve as expected, or in typical circumstances), and the sudden realisation—based on some environmental cue or trigger—that something other than what the decision maker expected was actually happening. The D/F model appears below as the left-hand portion of Figure 1, and charts the pathways for elaborating, questioning, or reframing understanding of the situation.

In the D/F model, the concept of a frame is invoked to denote an explanatory structure that defines entities by describing their relationships to other entities. Like other schema- or template-based models, and very like like Hatano and Inagaki's notion of a data-model mechanism, a frame is both a structure for interpreting the data as well as a lens or guide in the search for additional data. Seeing the data-frame relationship as reciprocal presents a number of challenges for the sensemaker, but also explains some of the complexities of interpretation and assessment of data. Data are not seen as primitives in the D/F model, but rather as inferences based on the current frame. Likewise, the frame is inferred from a few key cues or anchors in the situation. The frame can be represented both mentally (such as a person's compiled experience or knowledge structure) and externally (e.g., as a narrative report, or a physical artefact, such as a map or diagram). The frame provides the basis for piecing together existing data, as well as filling in (i.e., making inferences) and revealing gaps in understanding (e.g., to guide future data collection requirements).

In some ways, the D/F model is conceptually similar to comprehension-based models of language (e.g., Kintsch, 1988). For instance, D/F offers a context-sensitive mechanism for how we form explanations about the current situation, to anticipate how the situation will evolve in the immediate future, and perceive the implications for action. Like some models of comprehension, the D/F model relies on inference as a key mechanism for understanding, However, unlike prior models (which focused primarily on text comprehension rather than situation understanding), the emphasis of D/F is on supporting our ability to detect and identify problems, make new discoveries and generate insights in a way (e.g., via abduction) that might suggest a solution strategy (Klein, 2003).

More specifically, Klein et al., suggested that individuals make sense of an atypical situation by either elaborating or questioning a frame, or by coming up with an entirely new frame (a process called re-framing). Elaborating a frame could be likened to Kintsch's construction-integration process in that it is a way to update the current situational representation. However, when faced with discrepant or inconsistent data (such as the lack of an expected event or an unexpected event) the D/F model proposes that questioning may follow noticing or being surprised by such data. For instance, a sensemaker might question their frame when some threshold for uncertainty is exceeded based on the growing number and/or nature of the discrepancies, or when an increase in effort is required to account for anomalous data. It is on this point that D/F and CFT converge: The tendency to fixate on and attempt to preserve the initial account or frame in a cognitively rigid manner, using knowledge shields to explain away or ignore contradictory data (see Feltovich et al., 2001).

The questioning of a frame supports the discovery of inadequacies in the initial account, which must then be addressed with respect to comparisons of alternative accounts, and/or re-framing of the initial account, perhaps replacing it with an alternative that is recognized from previous experience. If no alternative is readily available one might have to be deliberately constructed based on the existing data and the new data that could not be accounted for in the initial account. Sometimes such analysis leads to an insight that an alternative might work better (see Klein, 2013 for a description of pathways to insight). During re-framing, inconsistencies and contrary evidence are not just accumulated, they guide the search for further data, support re-assessment and re-interpretation of old data, and redefine what counts as data.

The D/F model evolved from research on larger scale sensemaking in organisations (Weick, 1993, 1995), used mostly in the context of post-hoc explanations of significant national and international events, and from recent cognitive task analytic studies of decision making (for related research on sensemaking in the field of Human-Computer Interaction, see Priolli & Russell, 2011; Russell, Stefik, Pirolli, & Card, 1993). Recent support for this model has come from assessments of high-level sensemaking in real-world decision contexts, including military intelligence analysis, medicine, business, firefighting, and academic influence (e.g., Baber et al., 2016; Pontis & Blandford, 2016; Sieck et al., 2004, 2007), as well as the coordination of sensemaking within teams of various kinds (Attfield & Blandford, 2011; Klein, Wiggins, & Dominguez, 2010). Although this evidence serves as verification of the original D/F model, studies are needed to confirm the hypothesis that adaptive framing is central to expertise in complex real-world contexts.

Given the dynamic nature of complex work, not only are changes in situational understanding often required, which include changes in the situation that require additional and corresponding changes in situational understanding, individuals also have to adapt their response or their plan of action to an evolving situation. Although many others have described how planning occurs at different levels of abstraction in different domains (e.g., Hayes-Roth & Hayes-Roth, 1979), the need to replan and to clarify, modify, and change goals during an operation has not been addressed in psychological (and many computer science) descriptions of planning.

Flexible Execution: A Means to Adaptively Replan

The flexible execution—or Flexecution—model of adaptive replanning (i.e., planning in stride) was developed to describe how individuals flexibly pursue goals in the types of complex settings that are characterized by emergent and unpredictable challenges (Klein, 2007a, 2007b, 2011). In particular, Flexecution was proposed as a means to capture how, when presented with unforeseen circumstances that render original objectives or plans superfluous, goals are redefined based on what is being learned as a plan is being executed. The Flexecution model of adaptive replanning is presented below as the right-hand portion of Figure 1 and illustrates the different kinds of pathways for elaborating or reframing goals.

Based on earlier work on adaptive teams (e.g. Klein & Pierce, 2001) and on the notion of adaptive planning or replanning (e.g. Klein & Schmitt, 1996; Ross et al, 2004), the Flexecution model was developed to address the identified limitations of a management-by-objectives approach to problem solving and planning. This approach assumes objectives identified at the beginning of the planning process would remain intact, and that any plan modifications would occur in pursuit of the same goals. In contrast, the Flexecution model evolved as a management-by-discovery approach where both courses of action and goals are adapted to meet the operational demands of goals that emerge dynamically, some of which conflict, are reprioritized, juggled, traded off, or become obsolete (Klein, 2011). Hence, a key feature of the Flexecution model is the recognition that goals change as actions unfold, and that plans must be flexible with respect to their ways, means (i.e., methods and resources for achieving an objective), and ends (i.e., the objectives themselves). Flexecution is, therefore, a model of adaptive planning (or re-planning), which accounts for what happens (after a plan has been developed and communicated to those responsible for executing the plan) when faced with the dynamics of the real-world. Although it has been noted for centuries that, in reality, replanning is typically necessary (see Helmuth Bernhard Graf von Moltke, 1800-1891), the Flexecution model is arguably the first to address this issue at any psychological depth.

Similar to the D/F model of sensemaking, Flexecution is a continuous activity where actions and objectives identified to meet the operational requirement are continuously evaluated. According to the Flexecution model, adaptive performance is achieved by doing; hence it can be termed performance by discovery. Actions employed to achieve a goal can lead to discovery of new aspects of a situation including previously unrecognized opportunities for action, and new ways of being successful. Action can also lead to emergent challenges, as well as inconsistencies or anomalies, and these must be detected, validated and understood with respect to the impact on meeting the overall intent of the actions.

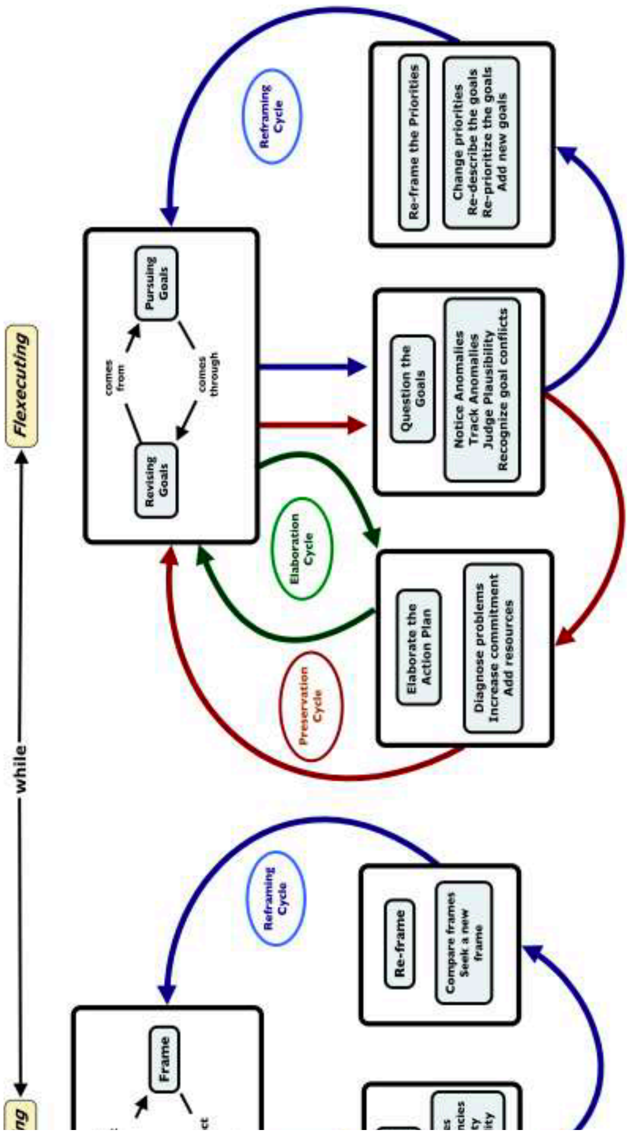

Figure 1. An integrated (DF + F) macrocognitive model of adaptive skill (Adapted from Hoffman, Best, & Klein, 2014; Hoffman & Hancock, 2016) which merges the Data-Frame (D/F) sensemaking model and the Flexecution (F) model of Adaptive Planning.

The model acknowledges the brittleness of plans and highlights that planning is often specified at an abstract or strategic level detailing only the overarching intent—primarily because identifying and specifying the objectives for a plan is challenging in ill-structured, complex, and dynamic situations. Moreover, such plans (including methods and goals) require on-the-fly elaboration and adjustment in order to bring about the desired outcome for resolving the operational problem (e.g., see Ward & Eccles, 2006). In addition, since goals or features of goals can be emergent in these types of settings, decision makers must be ready to both modify or change their course of action or goals in order to meet the changing demands. Sometimes, however, the goals or plans must be reframed, and also traded-off against one another (e.g., Hockey, 1997) in terms of the level of aspiration for success. This happens through a continuous assessment and re-assessment of the situation and progress toward intended outcome. This can be done by flexibly changing priorities, adding new or deleting/refining existing goal properties, reducing the commitment to and effort associated with a goal, or even identifying new goals in order to achieve the intent. This is particularly true when the work requires coordination and cooperation with other intelligent, adaptive actors or with an intelligent adversary.

Klein and colleagues have identified several key challenges to effective flexecution. First, actors must be able to gauge progress, both in terms of the need to adapt and the effectiveness of any adaptation with regard to achieving intent. Second, flexecution contributes to the in-event system coordination burden, requiring effective communication among actors. Third, gauging progress and coordination on the fly create potential risks that also must be managed, such as managing the trade-offs associated with goal de-confliction. This can require the application of additional skills, such as collaboration and coordination, anticipatory thinking, contingency planning, and crisis management (e.g., see Hollnagel, Woods, & Levenson, 2006). Fourth, initial planning is often accompanied with an investment in that plan, especially the mustering of resources, and so there is often a reluctance to change. Although the time invested in the initial planning process can be leveraged when re-planning, planners have to invest additional effort to overcome the inertia against change and adaption. Finally, the absence of practice in overcoming these challenges is likely to make it harder to adaptively re-plan. Hence, creating opportunities to build skill in these areas is vital. Encouragement and authority to explore during training alternative goals, methods, procedures, and strategies—and to practice flexecuting between them in a context-sensitive manner—is likely to lead to less brittle systems and greater organizational learning. Moreover, skill at adaptation and authority to adapt in-event is likely to be the basis, at least in part, of system resilience (e.g., Hatano & Inagaki, 1984; Hollnagel & Woods, 1983; Hollnagel et al., 2006).

The evidence for the Flexecution model came primarily from research on military planning. Initially, evidence was gathered from work underscoring the challenges of wicked problems (Klein & Weitzenfeld, 1978; Klein, 1996; Dorner, 1996; Brehmer, 2005) and from field research based on exercises with military planning teams (Klein & Miller, 1999; Klein et al., 1996; Schmitt & Klein, 1999; Ross et al., 2003a, 2003b). Its precursor, the recognitional planning model, has also fueled work by others to look at rapid re-planning in complex operational environments (Thunholm, 2005; Cheah et al., 2005). Although the Flexecution model has been used to sensitize planners to the challenges of planning operations in military command and staff colleges, and recommendations have been suggested for doctrine, processes and operating procedures in this domain (e.g., Hoffman & Shattuck, 2006; Thunholm, 2005; Schmitt & Klein, 1999; Ross et al., 2004), the empirical evidence has been slow to emerge. Regardless, in complex domains such as defence, there is a recognition that critical thinking and.

cognitive skills—that underpin both sensemaking and flexible execution—are critical to leadership and the ability to adapt. For instance, the future character of conflict, which has been proposed to be an increasingly dynamic technological environment that presents challenges and opportunities for the way we and our enemy work, demands both successful adaptive thinking and adaptive performance. Research to test the Flexecution model would be valuable for adaptive expertise training programs

As a means to describe a way in which adaptive skill can be conceived, Hoffman and colleagues recently proposed a unified conceptual model of macrocognition that directly integrates the D/F model of sensemaking and the Flexecution model of adaptive replanning (see Hoffman, Best, &Klein, 2014; Hoffman & Hancock, 2016). This is shown in Figure 1. This model illustrates that skilled adaptation through sensemaking and replanning is both an iterative and interdependent process. In the next section, we discuss how this model and the associated research was used as a means to elaborate on the practical definition of adaptive skill from a stakeholder's perspective and as a basis for developing training principles designed to improve adaptive skill.

A Stakeholder's View of Adaptive Skill and Elaborated Definition

Several defence-related efforts are currently ongoing with respect to developing adaptive skill and adaptive leadership that would benefit from an understanding of this model, and/or basing training on principles that emerge from it and the associated literature. For instance, the U.S. Department of Defence has identified adaptive skill as being critical to both success and expertise, and have developed a mandate to improve adaptability (see United States Army, 2011). Similar efforts have been ongoing in the United Kingdom for some time (e.g., see Ward et al., 2016a). For instance, the Royal Military Academy, Sandhurst, have developed case-based scenarios as a means to develop adaptive thinking as part of the British Army initial officer training. Likewise, the Royal Naval College, Dartmouth, and The Royal Air Force are currently revisiting their thinking skill requirements. However, there has been no consensus within these services, or across stakeholders more broadly, about what exactly is meant by adaptive skill, or guidance sought on how to develop the cognitive skills responsible for successful adaptation (e.g., Gore & Conway, 2016).

To progress and remedy this situation, we solicited definitions of adaptive skill from a range of defense-related stakeholders, in the context of their current roles/service. Fourteen definitions were submitted, each containing multiple components. These were clustered into four themes, three of which had considerable support among the stakeholders: (a) Change based on situational dynamics (Action); (b) Evaluation of actions relative to goals/intentions/current context (Meta-Cognitive/Regulatory Skill), and; (c) Cognitive-situational influences (Understanding). These themes are consistent with our previous analysis of definitions in the literature. The fourth theme (labeled "other") did not receive as much support, but it highlighted some potentially important issues: Adaptation may occur at any level within the work system (e.g., organization, teams or individuals), and; opportunities for and/or authority to change were likely to influence adaptation. In addition to exposure to system variability, these two factors (opportunities for and authority to change) had been identified as key constraints on adaptation by Hatano and Inagaki (1984/1986). Accordingly, we proposed a revised definition of adaptive skill, which has been updated here (in italics):

> Timely changes in understanding, plans, goals, and methods in response to either an altered situation or updated assessment of the ability to meet new demands, that permit successful efforts to achieve intent (Ward et al., 2016a, p.20), *or*

> *successful efforts to realize alternative statements of intent that are not inconsistent with the initial statement but more likely to achieve beneficial results under changed circumstances.*

This revised definition of adaptive skill captures the action-based changes in situational dynamics, cognitive changes in situational understanding, and the meta- and regulatory-level evaluation of actions and goals relative to one's intentions and the current context. At an abstract level, this definition is consistent with the aforementioned definition of Macrocognition as adaptation to complexity (Hoffman, et. al., 2014) and the derivative proposed to describe expertise: skilled adaptation to complexity. It is also consistent with the integrated model of macrocognition (see Figure 1). It captures the requirement for understanding in messy, complex, and dynamic environments, which can be thought of as sensemaking. Moreover, the execution of action can be thought of as a process of adaptive re-planning or flexecution, in which plans and goals are pursued and revised iteratively in response to changes in situational context. The integrated D/F + F model (Figure 1, above) illustrates that these two components are not only integral to a conceptual model that instantiates any useful definition of skilled adaptation to complexity, but is a confirmation of the interdependence between D/F + F components. This interdependence, which can be thought of as managing the tradeoffs within and between these components, is necessarily a highly metacognitive and regulatory process. Hence, future research should consider the D/F + F integrated model as a starting point for future theoretical and empirical research on understanding and developing adaptive skill. In the final section of this paper, we present several adaptive skill training principles that are derived from the aforementioned macrocognitive literature and the integrated model.

Training Adaptive Skill

Fundamental to the achievement of adaptive performance is the opportunity for practice at problems that stretch current competency. Such practice permits acquisition of knowledge and reasoning skills exercised in differing situations or contexts (i.e., varieties of tough, rare tasks sampled from across the span of possible operational contexts) in safe-to-fail environments. This would include the types of activities considered deliberate practice (e.g., Ericsson, Krampe, & Tesch-Romer, 1993) and deliberate performance (Fadde & Klein, 2010). Also fundamental is practice at revising one's conceptual understanding. That is, practice is needed that extends current knowledge and facilitates acquisition of new knowledge and reasoning skills to support task performance at the boundaries of current understanding. In addition, practice is needed at reformulating that knowledge and modifying related skills and strategies to fit differing situations or contexts on either side of the aforementioned knowledge boundaries.

Hoffman et al. (2014) conducted an extensive review of the existing training and learning literature, and based on the available evidence, highlighted the primary goals of any training program designed to create understanding that facilitate the achievement of high levels of proficiency, including adaptive capacity. They asserted that training needs to:

(i) Exploit learning strategies and conditions that facilitate robustness, resilience and adaptivity (e.g., interleaved or spaced practice, desirable difficulties, context variability/ecological sampling, transfer appropriate processing);

(ii) Mitigate the reductive tendency to oversimplify understanding of complex phenomena, unnecessarily;

(iii) Reduce cognitive rigidity (i.e., tendency to avoid change or learning);

(iv) Identify boundaries of current mental models where current strategies and skills fail and acquired rules are inadequate;

(v) Reconfigure understanding by unlearning misconceptions, and learning new/changing old conceptions;

(vi) Stretch skill by using proficiency scaling to determine the appropriate level of challenge for given trainees;

(vii) Identify tough cases that characterise the need for adaptation and success at the expert level;

(viii) Compress training by creating and facilitating access to tough-case repositories—where exposure can be increased, contextual dependencies learned, key concepts mapped across dis/similar cases, and anomalous cases leveraged for adaptive learning;

(ix) Provide rich process and outcome feedback (especially on tough cases), and opportunities to learn from expert mentors and exploit lessons learned, by modelling and adapting expert reasoning strategies and skills across dis/similar cases.

Paradoxically, as the knowledge shields concept would have it, a well-developed conceptual understanding or mental model can actually make it more difficult to accept the need to update that conceptual understanding further because it already allows practitioners to do a good job most of the time. As a result, it can be easier to hold on to this knowledge because it is usually correct, and can be easier to find reasons *not* to change or to find ways of explaining away contrary data (i.e., to use knowledge shields).

Many of these ideas are based on the empirical research on expertise and the numerous studies adopting a macrocognitive or human-machine systems approach (see Hoffman et al., 2014). Overcoming cognitive rigidity, the need for flexible knowledge acquisition, and the active construction of knowledge assemblies emanate from Cognitive Flexibility Theory and the associated evidence, and a related theory, Cognitive Transformation Theory (CTT; Klein & Baxter, 2009). CTT is focused on the unlearning of strategies. Where much expertise research has focused on identifying the cues, patterns and strategies used by experts, and some researchers have tried to develop training programs to teach people to think like experts, few, if any, have attempted to develop skills training that teaches people how to *learn like experts* (Klein, 1997, p. 37); that is, how they deliberatively develop their proficiency. Recent work by Klein and colleagues have employed a technique called ShadowBox to try and do just this (Klein & Borders, 2016; see also Ward et al., 2008; Ward, Suss, & Basevitch, 2009).

In a recent extensive review of the expertise and training literature in complex and dynamic environments (Hoffman et al., 2014, p.137), we merged the core ideas of these two theories (Cognitive Flexibility and Cognitive Transformation [CF-CT] Theory merger) into a single set of postulates and principles. These emphasize the active and flexible nature of learning, and the limitations, and incomplete nature of mental models. Moreover, they reiterate the self-reinforcing nature of reductive tendencies which are preserved through misconception networks and knowledge shields, which often lead to incorrect diagnoses and enable the discounting of evidence and alternative explanations. Training must support the learner in overcoming these phenomena and associated effects. Hence, training to develop adaptive skill, by definition, is likely to require some degree of unlearning and/or relearning and, therefore, likely requires at least some engagement in a safe-to-fail environment. Moreover, advanced learning is likely to be promoted by emphasizing the interconnectedness of multiple cases and concepts along multiple conceptual dimensions, and the use of multiple, highly organized representations.

Training that leverages these characteristics has already been shown to be effective in accelerating the development of expertise, largely by various researchers within the NDM community (see Hoffman et al., 2014; Klein et al., 2001; Klein Associates, 1999). We expect that these training methods can promote development of the types of skills that are consistent with the notion of adaptive skill. For instance, one example of training requirements to develop adaptive skill was proposed by Lazzara et al. (2010). Their recommendations included: Cue Recognition Training (i.e., proactive prompting toward most/least important cues and debriefing focused on the process that led to misinterpretation and non-detection); Sensemaking Training (i.e., assigning meaning to and providing process feedback about contextual cues); Planning and Forecasting Training (i.e., developing contingency plans/alternative courses of action that require consideration of potential second- and third-order effects); Self- and Team-Metacognitive Skills Training (i.e., reflecting on comparison of trainees' and experts' mental models); and Error-based Training (i.e., error-management instructions for more advanced trainees).

The primary aim of these training requirements has been to help trainees develop better mental models by identifying gaps in their performance and thinking, and providing expert models from which learning can be scaffolded. It has also been to help more advanced trainees recognize when errors occur, cope with the negative aspects of committing errors, and to learn how to prevent them. In the next section, we propose six training principles that should facilitate the development and acceleration of adaptive performance skill (see also Ward, 2014, 2015).

Adaptive Skill Training Principles

Principle 1: Flexibility-Focused Feedback

Training for adaptive performance should provide feedback that promotes cognitive flexibility (e.g., Klein & Baxter, 2006; Feltovich et al., 1997). Training should:

- Help overcome the natural inclination towards cognitive rigidity, i.e., to put up knowledge shields, or generate reasons not to change;
- Help unlearn concepts that incorrectly simplify understanding of the domain/skill;
- Facilitate learning of to-be learned material by allowing it to be experienced, acquired, taught, organised, and/or mentally represented in different ways.

This type of feedback relates to anything that permits learners to overcome the human tendency to rigidly stick with current methods, especially when the situation changes or when there is a misunderstanding about why and when those methods work. Feedback given during learning opportunities should permit learners to: (a) learn when their current strategies work effectively and when they do/will not; (b) promote the development of new strategies and conceptions that permit them to demonstrate effective flexibility and adaptation to new situations, or to unexpected changes in the training exercise or learning experience; and (c) quickly re-assess and re-appraise their current interpretation of a situation so that they can reassemble current knowledge of a situation in flexible ways (including adding to it, subtracting from it, or even abandoning it entirely in favour of a new conception). Such feedback need not be immediate since delayed feedback provides the learner opportunity to reflect on errors and mistakes (see Hoffman et al., 2014).

Principle 2: Concept-Case Coupling

Training for adaptive performance should provide opportunities for learners to experience the full variation of ways in which a given learning concept is manifested in particular cases (Bransford et al., 1990; Coulson & Feltovich, 1993; Hatano & Inagaki, 1984/1986; Healy et al., 2006; Lesgold & Nahemow, 2001). This permits cognition and context to be reconnected. Specifically, training for adaptive performance should:

- Map the important relations between to-be-learned concepts and the cases in which these concepts are applied (across training / work contexts) in a manner that is readily apparent (e.g., salient, meaningful, useful, valuable);
- Facilitate experience of how concepts vary in situ from case to case by sampling multiple cases from the full range of possibilities, especially those not yet experienced, and facilitating exposure to both situational and action variants of any given concept and their reciprocal effects;
- Promote value in understanding the system constraints that require adaptation, and provide authority to actively experiment with varied cases.

When aspects of adaptive performance and cognitive skills are presented in training, they must be presented in conjunction with the situational factors that demand adaptations. Not only that, but the full range of situational contexts should be sampled in order to illustrate the structural patterns in the situations that trainees must understand and pay attention to, in order to minimize the future transfer distance between what they know and the situation to which they have to adapt (i.e., the future case to which they have to apply that concept). The more cases in which a concept is experienced, and the more varied the cases experienced, the more likely that concept will be learned flexibly, and adaptive skill developed.

Principle 3: Tough Case Time Compression

Training for adaptive performance should design out naturally occurring time lags and gaps between cases to increase frequency of challenging learning opportunities (e.g., Crandall et al., 2006; Ericsson, Whyte, & Ward, 2007; Hoffman et al., 2014). Training should:

- Focus on tough cases (i.e., difficult/challenging and/or rare/low-frequency cases);

- Present dilemmas to trainees—for instance, an unexpected event, a situation where there is no clear right or wrong solution, and/or there is a need to change the planned or current course of action;
- Increase a learner's exposure to the gamut of tough cases in all of their guises;
- Compress training time via facilitated access to a bank of such tough cases derived from knowledge elicitation with experts;
- Manage the trade-off between tough-case training activity and the potential negative consequence in terms of mental effort and fatigue.

In a similar vein to simulation-based learning (e.g., see Hoffman et al., 2014; Ward et al., 2006), time compression via a test bank of tough cases provides the opportunity to increase the frequency with which learners can practice, especially practice at coupling concepts with cases and variants of those cases. This is particularly important for those tough cases where most practice is needed, especially when one considers the many ways in which tough cases may vary. Incidentally, it should be noted that the process of creating a test bank is tantamount to the process of capturing and preserving expert knowledge, which is itself a worthwhile endeavour that can contribute long–term to the establishment of adaptive organizations (See Hoffman et al., 2014).

The extent and complexity of case variation—potentially involving multiple dimensions—is likely to contribute to their being considered tough. Compression permits training and instructional designers to design out naturally occurring, long, time gaps between cases to afford a greater frequency of learning opportunities. It also permits them to increase exposure rate to low-frequency cases that would otherwise take a considerable amount of time during normal training and/or ordinary work flow to accrue the necessary experience to develop adaptive skill.

Principle 4: Case-Proficiency Scaling

Training for adaptive performance should ensure that cases are tailored to current needs and proficiency levels to stretch performance just beyond that which is currently attainable (e.g., Chi, 2013; Ericsson & Ward, 2007; Klein & Borders, 2016; Hoffman, 1992; Hoffman et al., 2014; Vygotsky, 1978). Specifically, training for adaptive performance should:

- Leverage training content from expert mental models;
- Scale test banks of tough cases to each specific proficiency level using zone of proximal development (ZOPD)-adjusted expert mental models. This will provide cases that are sufficiently challenging and permit current skills to be stretched most effectively;
- Maintain training at the edge of the ZOPD, which is a moving target as individuals learn and improve.

There is a clear need for training to be based on expert mental models (e.g., Klein & Borders, 2016). However, when learning complex cognitive tasks, presenting the expert model in the form of an expert articulated explanation alone facilitates learning only minimally and does not noticeably improve transfer (see Chi, 2013; Schwartz & Martin, 2004). A better approach is to have the trainee create an expression of their own understanding (e.g., via text or diagram) and then see the expert's description. Then, the expert's model, including an explanation of their reasoning, needs to be supplemented with a means to scaffold the difference between the trainee's current mental model and the expert's model. This means that expert explanation may need to be adjusted based on the trainee's current level of proficiency to facilitate development of strategies relevant for their own ZOPD (Vygotsky, 1978)—that is, not too easy and not too hard. This highlights one of the key difficulties in training and instructional design literature: knowing how much expert scaffolding to provide to the learner at each proficiency level, in what form, and the extent to which, and when exactly, that scaffolding or guidance should be faded (Koedinger et al., 2008). A recommendation to simply fade scaffolding or guidance as individuals improve is only of very limited help. A specific recommendation from Hoffman et al. (2014) was to rely on expert mentors to provide both expert guidance and active learning experiences—concepts that are advocated by CTT and CFT.

Hoffman and Ward (2015) recently summarized the characteristics of good mentors. These included but are not limited to: fostering a supportive learning environment; providing diverse learning opportunities; varying contextual constraints; emphasising the interconnectedness of cases and concepts along multiple conceptual dimensions; employing various strategies for conveying knowledge; sharing their own knowledge and skill, and modelling expert behaviour and thinking in a context-sensitive manner; forming a rich mental model of the learner's own knowledge and skill to anticipate their difficulties, and support recognition of the learner's misconceptions and identification of the boundaries of their own understanding. In addition, good mentors, help devise practice activities that afford the kind of feedback necessary to push those boundaries and address current reductive tendencies. They also provide support for the kinds of experiences synonymous with operating in complex environments, such as increased uncertainty and cognitive load, high levels of stress and frustration associated with exploring the boundaries of their mental models, and aid in managing goal conflicts and changing priorities.

These characteristics and behaviors of a good mentor not only facilitate implementation of this principle (i.e., case-proficiency scaling) but also speak to the implementation of the other principles. Although other facets of mentoring and coaching (e.g., psychosocial support) have been popularized in the literature, the evidence is limited on the extent to which these other functions contribute to professional development, skill learning, and expertise development in particular (for a review, see Petushek et al., in press).

Principle 5: Complexity Preservation

Training for adaptive performance should preserve the complexity of the situations in which learning takes place and/or complexity of the knowledge, methods, strategies and skills to be learned (e.g., Bonsangue, 1993; Feltovich et al., 1989, 1993, 2001; Lesgold et al., 1992; Spiro et al., 1989):

- Do not oversimplify. Instead, training should provide opportunities to facilitate adaptation to complexity, novelty, and changing demands and goals;
- Shift conceptions of learning from knowledge storage and knowing more to thinking differently, flexibly, and dynamically. Learners should practice…
    - In varied contexts,
    - At boundaries of current knowledge and skills,
    - Accessing knowledge *when* it is useful/needed,
    - Anticipatory thinking, and consider the implications of the current situation for the future, and the alternative ways in which situations may evolve,
    - Updating and reconfiguring understanding "on the fly" and constantly!
    - Juggling priorities and goal-conflict resolution.

Task decomposition, simplified learning, and increasing the complexity of a task incrementally may be appropriate for learning fixed, simple and/or procedural tasks, or schoolhouse learning. However, this method may limit understanding of complex interactions on real world, highly complex, and dynamic domains, effectively forcing trainees to learn how to make reductive sense of phenomena that do not accurately reflect how they are manifest in the real world.

When domains are complex and ill-structured, a different approach has been to teach people to learn like experts learn (Klein, 1997): to deliberatively learn to actively assemble knowledge from different conceptual and case sources rather than to learn to store and retrieve knowledge. This complexity-preservation approach emphasises the need for case-based learning in those domains that require an understanding of the situational dynamics, interacting processes, simultaneous events, emergent properties, and nonlinear causation, all of which are particularly difficult for learners to handle (see Hoffman et al., 2014).

Principle 6: Active Reflection

Training for adaptive performance should facilitate the use of metacognitive skills and reflective practice immediately prior to, during, and/or following work (e.g., Fadde & Klein, 2010). Training exercises should:

- Help the learner calibrate their own understanding of their skills, knowledge and understanding by predicting or estimating their competency, performance and/or learning (e.g., how long it will take to complete or learn a task, the level of performance that was/will be attained) relative to their actual (future or past) performance level and/or learning rate;
- Help the learner elaborate on their current understanding of their own representation of the problem space by engaging in:
    - Experimentation with new cases, contexts, situations, methods, strategies and response actions,

- Extrapolation (rather than interpolation) of experience with prior incidents to new incidents,
- Explanation (to self, to others, and by others) of what happened, why, and if/how success was achieved.

Experts, skilled at adaptation, are more likely to be well calibrated. They know what they know and know what they don't know—at least more so than those who are less proficient. Therefore, they are more likely to be able to self-diagnose current knowledge boundaries, and can better determine what they need to work on to improve their work performance. Furthermore, they are likely to make good predictions about their performance when adaptation is needed and/or make more accurate judgments about their ability to learn to adapt to the new circumstance. Similarly, experts are more likely to engage in active experimentation, sometimes as an essential part of their work. In particular, experts are more likely to engage with variants of cases and/or with variations in their course of action repertoire (see Hatano & Inagaki, 1984/1986). Sometimes, experimentation is pursued simply to find out what happens. At other times, it is used to see if something will work or to assess the associated effects of an intended change. At others, it may be to compare alternatives to find more effective methods (or to identify when situation-specific methods will be more effective). Rather than just leverage the methods employed in a prior incident to a new incident, extrapolation also permits lessons learned to be applied to real and/or imagined events, situations or contexts – to avoid doing things in the same way necessarily and to explore how prior lessons learned can inform the development of alternative methods and ensure future success. Estimation, experimentation, and extrapolation can generate opportunities for reflective explanation, to obtain a better understanding of the causal factors underpinning success, rather than of accuracy per se, since a definitive answer does not always exist (Fadde & Klein, 2010).

Current work is underway to instantiate some of these principles in concrete interventions, and to test their efficacy at a Defence educational establishment in the United Kingdom with mid-grade military Officers. Initial pilot work at a recent joint force exercise with an operational UK military headquarters suggest that these principles hold much promise for developing adaptive skill.

Conclusions

We have presented a case that adaptive skill is the *conditio sine que non* of expertise, and that skilled adaptation to complexity is most likely achieved by developing the kinds of conceptual skills and mechanisms represented in the integrated macrocognitive model. The integrative model combines the D/F model of sensemaking and the Flexecuition model of replanning, along with the core concepts in Cognitive Flexibility Theory and Cognitive Transformation theory, all of which are based on data on how experts operate in complex and dynamic environments where adaptation is key to success.

It has not escaped our notice that there are some apparent contradictions built into the literature. For example, the argument that the reductive tendency might apply to experts seems at odds with the claim that experts "know what they don't know." Similarly, the notion from Cognitive Flexibility Theory that complexity should not be reduced during training seems at odds with the notion of progressive complexification. Research on these and other ideas may contribute significantly to the science of Expertise Studies at the same time that it contributes to the establishment of methods for accelerated training.

The training principles we listed advocate the use of learning opportunities on challenging and non-routine cases, that are based on the expert's lived experiences, and that are problem-focused, collaborative, and led by skilled facilitators. These principles encourage learners to engage in the use of critical thinking skills and to make learning context sensitive. The principles advocate for the customization of learning through appropriate proficiency scaling, and to enhance face-to-face learning opportunities by exploiting and blending with appropriate technology, such as online systems, simulation, virtual reality, and educational gaming technology as necessary. There is strong evidence that training that leverages the above principles is effective in accelerating the development of proficiency, and there is suggestive evidence that these principles can promote development of the kinds of skills and characteristics (i.e., understanding, flexible action and meta-cognition/self-regulation) that are consistent with the notion of adaptive skill.

The outstanding challenge for future work is to translate these principles into concrete training objectives, course designs, student assessment and course assurance schemes. The intended impact of this review is to support policy and guidance decisions for training and education in the area of developing the complex cognitive skills that support building the adaptive nature of expertise and skilled adaptive performance (e.g., Gore & Conway, 2016). Previously, we have laid out a roadmap for how to design, implement and evaluate a program along the lines suggested here (see Hoffman et al., 2014). We welcome future systematic and programmatic efforts to help lay this groundwork.

Notwithstanding a number of gaps in the empirical evidence to support the effectiveness of existing training approaches aimed at enhancing adaptive performance, there is an operational imperative (in high reliability related organizations in particular) to continue to improve the development of adaptive individuals and teams (Zheltoukhova, 2014). The principles we have listed directly address Salas et al's (2017) call that future research should shed light on personal characteristics and organizational practices which lead to adaptation and resilience within individuals and teams. Crucially, the evidence of the effectiveness of the training principles is sufficient to warrant further development and testing in a range of contexts.

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